Connection to 0nbb and other Nuclear Physics Experiments

- BRIEF $0\nu\beta\beta$ Motivations
- $0\nu\beta\beta$ Experiments and Sites
- Future $0\nu\beta\beta$ and Underground Facilities
- Solar, geo-, and other low-energy neutrinos
- Other nuclear physics underground

There is No "Standard" Model

- ν mass requires either addition of fields to SM Lagrangian

e.g. $L \sim m_D \overline{\nu_L} \nu_R$

- ν mass allows $\overline{\nu_i} = \nu_i$ (Majorana neutrinos, $L \sim m_M \overline{\nu_R^c} \nu_R$)

Which in turn allows new CP-violating phases:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Dirac phase}} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{\text{Majorana phases}}$$

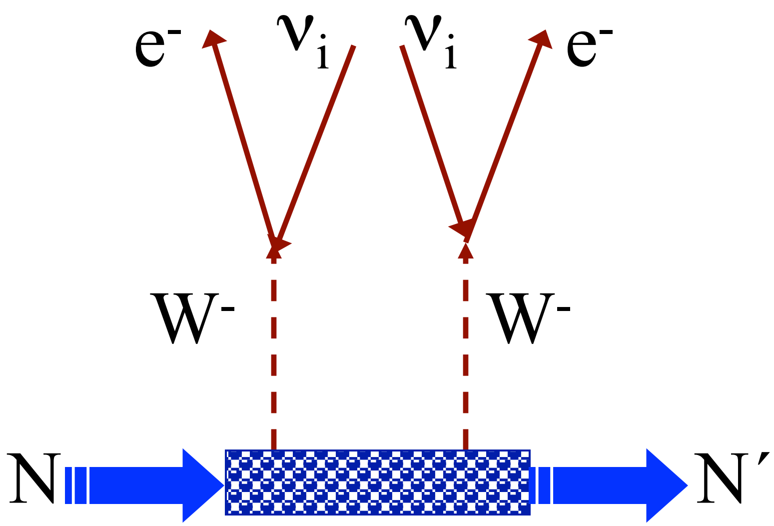
Majorana CP + heavy N_R + ... = Origin of matter/antimatter asymmetry?

Lepton number is a global symmetry…there is no *gauge* symmetry that prevents neutrinos from being Majorana.

If neutrinos are Dirac,
matter and antimatter are fundamentally different

Majorana Nature and m_ν

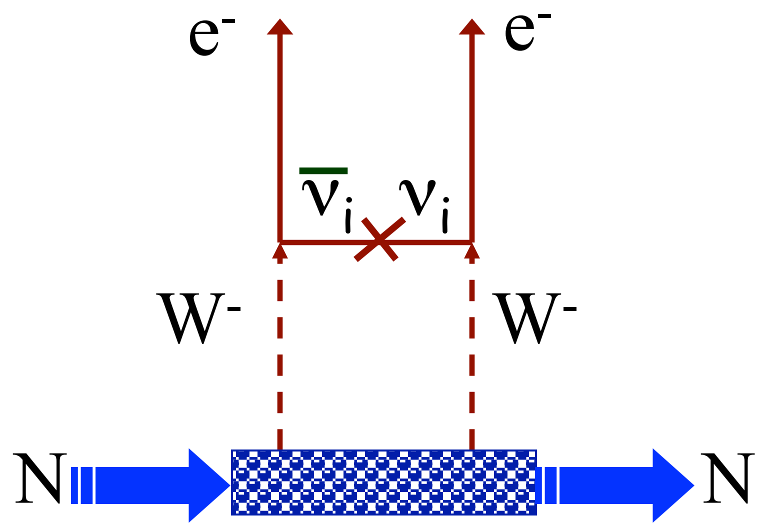
- $2\nu\beta\beta$ vs. $0\nu\beta\beta$



$$\Gamma_{2\nu} = G_{2\nu} |M_{2\nu}|^2$$

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

Allowed in some even-even nuclei



Nuclear matrix element (hard)

Phase space (easy)

$$T_{1/2} \propto m_\nu^2$$

$$\boxed{\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 m_\nu^2}$$

Mass is mixed average, including phases

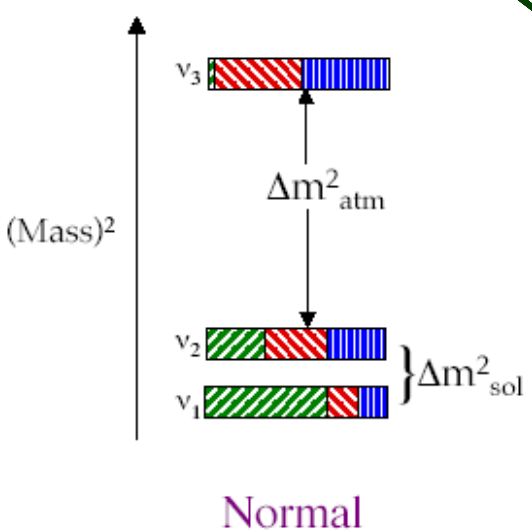
$$\langle m_\nu \rangle^2 = \left| \sum_i^N U_{ei}^2 m_i \right|^2 = \left| \sum_i^N |U_{ei}|^2 e^{\alpha_i} m_i \right|^2$$

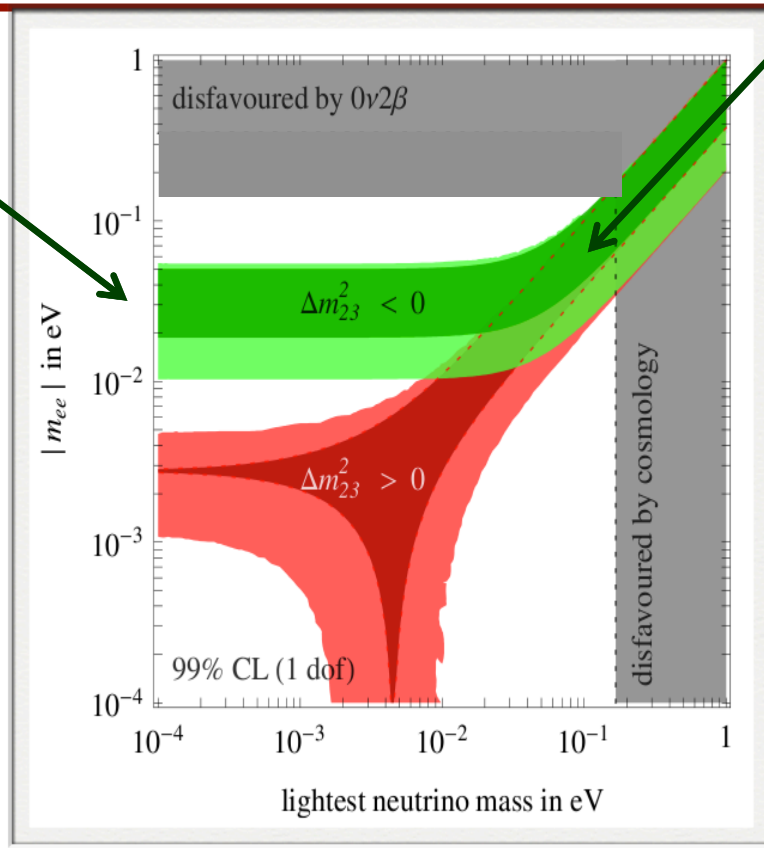
Elliott & Vogel, Ann. Rev. Nucl. Part. Sci. **52**, 115 (2002)

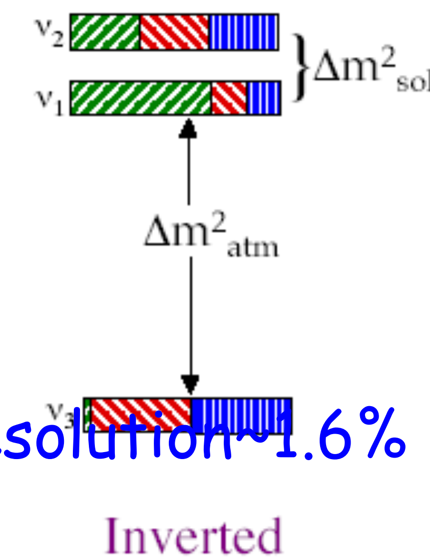
$0\nu\beta\beta$: Majorana Nature and m_ν

➢Desired Limits

We `hope' that either mass hierarchy is "inverted" or masses are somewhat degenerate.







Resolution~1.6%

$$(m_{\beta\beta} \equiv m_{ee} \equiv \langle m_\nu \rangle \equiv m_\nu)$$

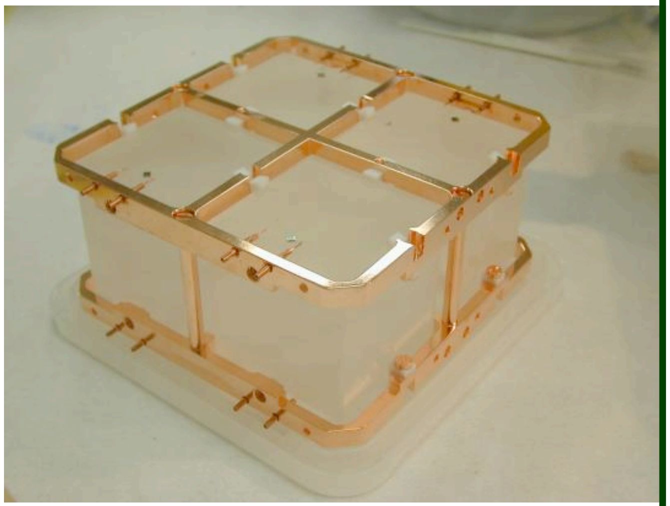
$0\nu\beta\beta$ Experimental Summary

Experiment	Isotope	Mass	Technique	Present Status	Location
EXO-200	^{136}Xe	160 kg	Liq. ^{enr}Xe TPC/scint.	Operating	WIPP
KamLAND-Zen (400)	^{136}Xe	400 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
GERDA	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Operating	Gran Sasso
CUORE-0	^{130}Te	11 kg	TeO_2 bolometers	Operating	Gran Sasso
MAJORANA	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Construction - 2013	SURF
CUORE	^{130}Te	203 kg	TeO_2 bolometers	Construction - 2014	Gran Sasso
KamLAND-Zen (1000)	^{136}Xe	1 ton	^{enr}Xe disolved in liq. scint.	Construction	Kamioka
SNO+ (0.3%)	^{130}Te	800 kg	Te loaded liq. scint.	Construction - 2014	SNOLab
SuperNEMO-Dem	^{82}Se	7 kg	^{enr}Se foils/tracking	Proposal - 2013	Fréjus
SuperNEMO	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal - 2019	Fréjus
nEXO	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SNOLab?
COBRA	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CANDLES	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
NEXT	^{136}Xe	100 kg	gas TPC	Development - 2014	Canfranc
1TGe	^{76}Ge	ton	^{enr}Ge semicond. det.	Development	
^{enr}CUORE	^{130}Te	600 kg	Enriched TeO_2 bolometers	Development	Gran Sasso
SNO+ (3%)	^{130}Te	8 t	Te loaded liq. scint.	Development	SNOLab
CARVEL	^{48}Ca	1 ton	CaF_2 scint. crystals	Development	Solotvina
LUCIFER	^{82}Se	18 kg	ZnSe scintillating bolometers	Development	Gran Sasso
AMoRE	^{100}Mo	200 kg	$^{40}Ca^{100}MoO_4$ Bolometers	Development	YangYang
MOON	^{100}Mo	1 t	^{enr}Mofoils/scint.	Development	
Mo Bolometer	^{100}Mo	350 kg	$ZnMoO_4$ Bolometers	Development	
GraXe	^{136}Xe		Scint. Liq. Xe within Graphene sphere	Development	
DCBA	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development	Kamioka
GSO	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development	
Quantum Dots	Various		Quantum Dots with isotope in liq. Scint.	Development	

Adapted from IF WG Summary (thanks to S. Elliott)

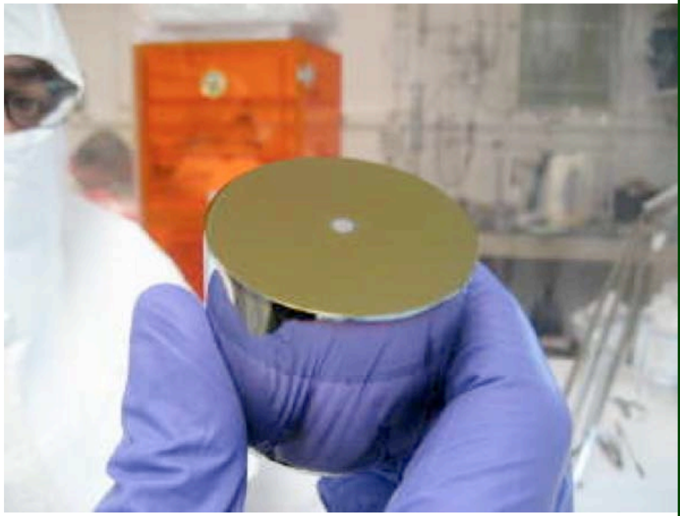
Experiments with US Involvement

CUORE



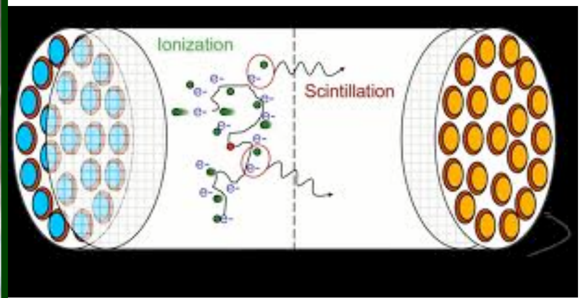
700 kg of TeO_2 crystal bolometers

MAJORANA



40 kg of high-purity germanium detectors

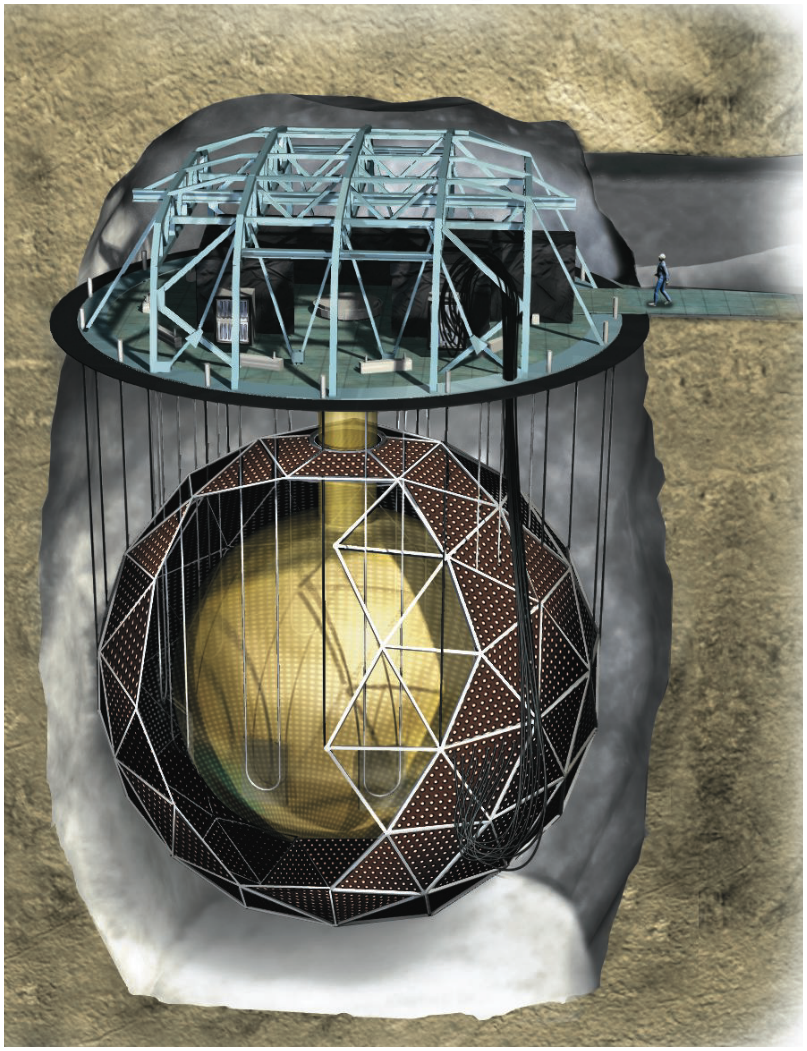
EXO



LXe scintillation and ionization

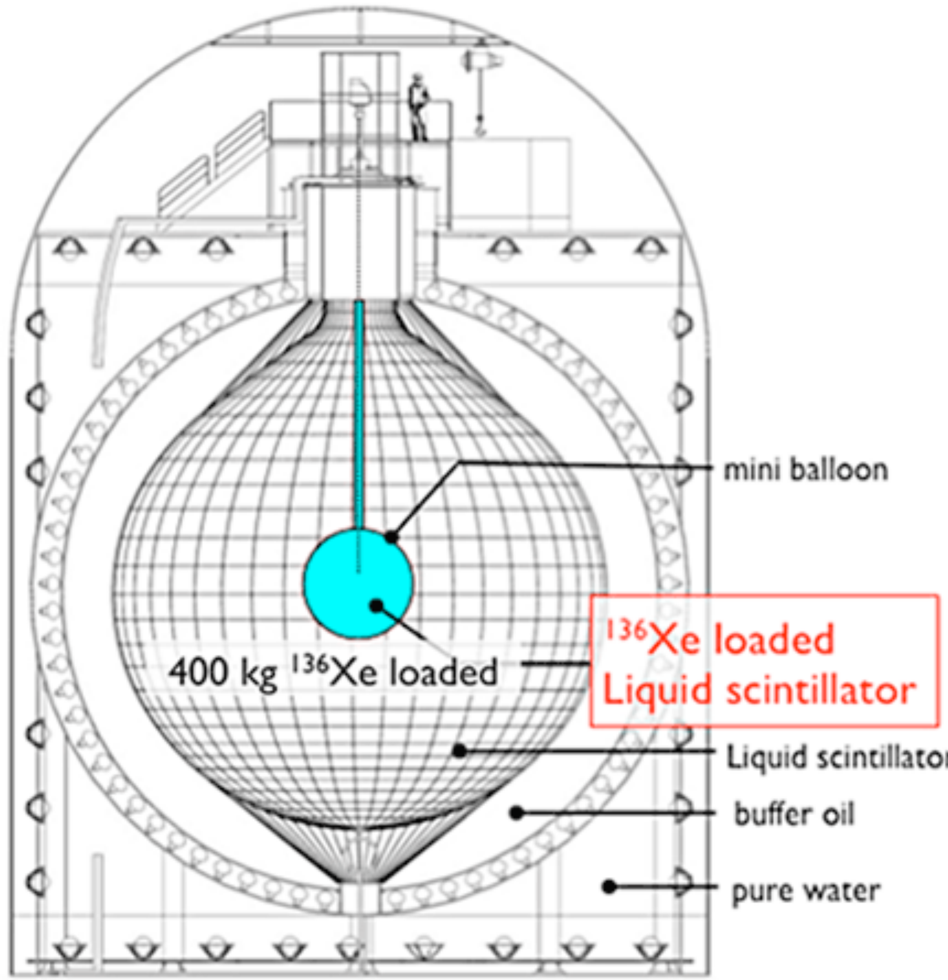
Experiments with US Involvement

SNO+



Te-loaded Scintillator

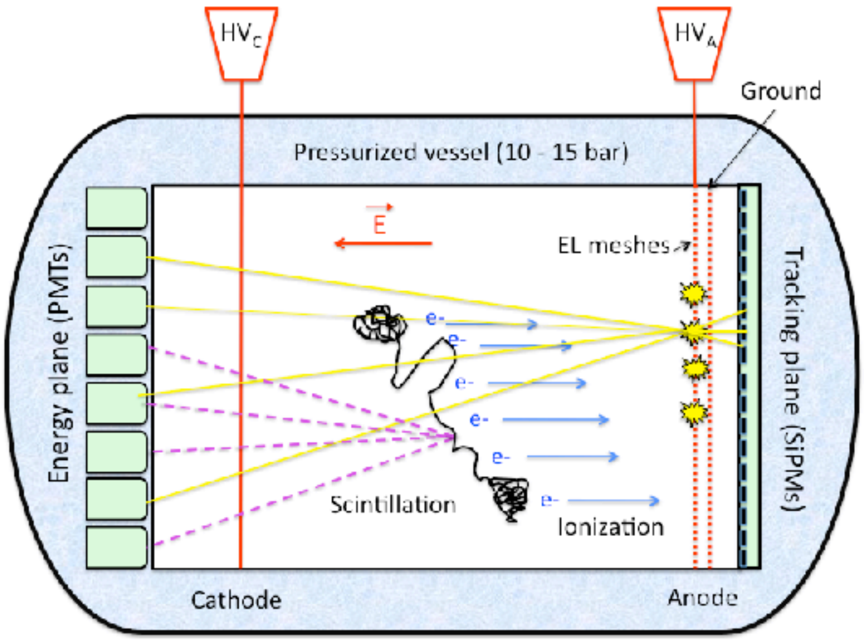
KamLAND-Zen



Xe-loaded scintillator

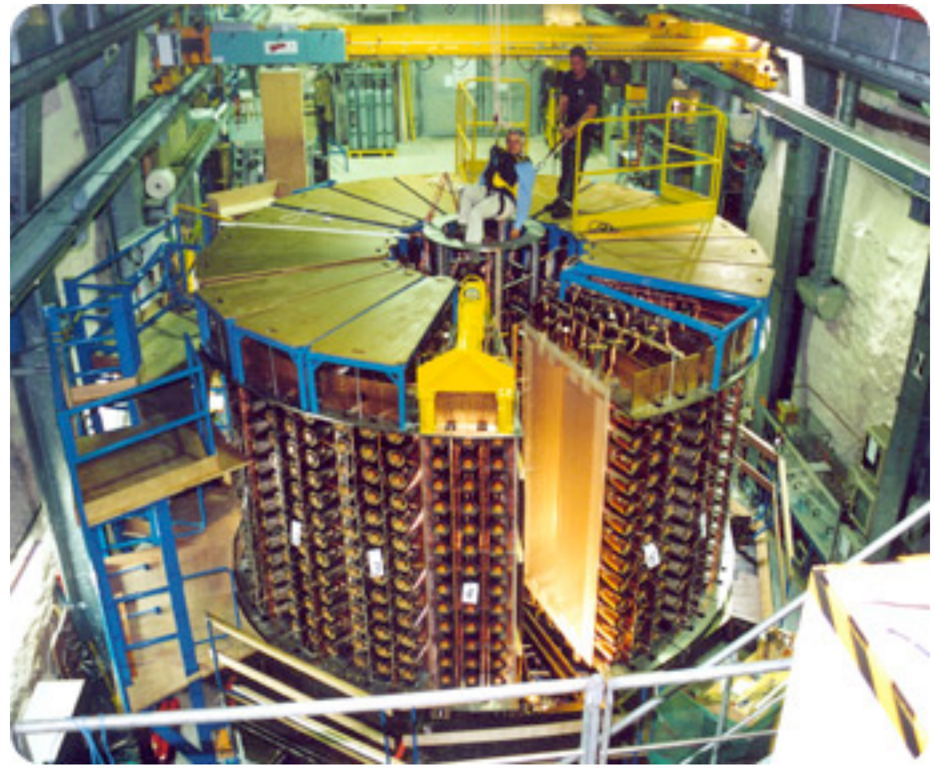
Experiments with US Involvement

NEXT



Xe TPC

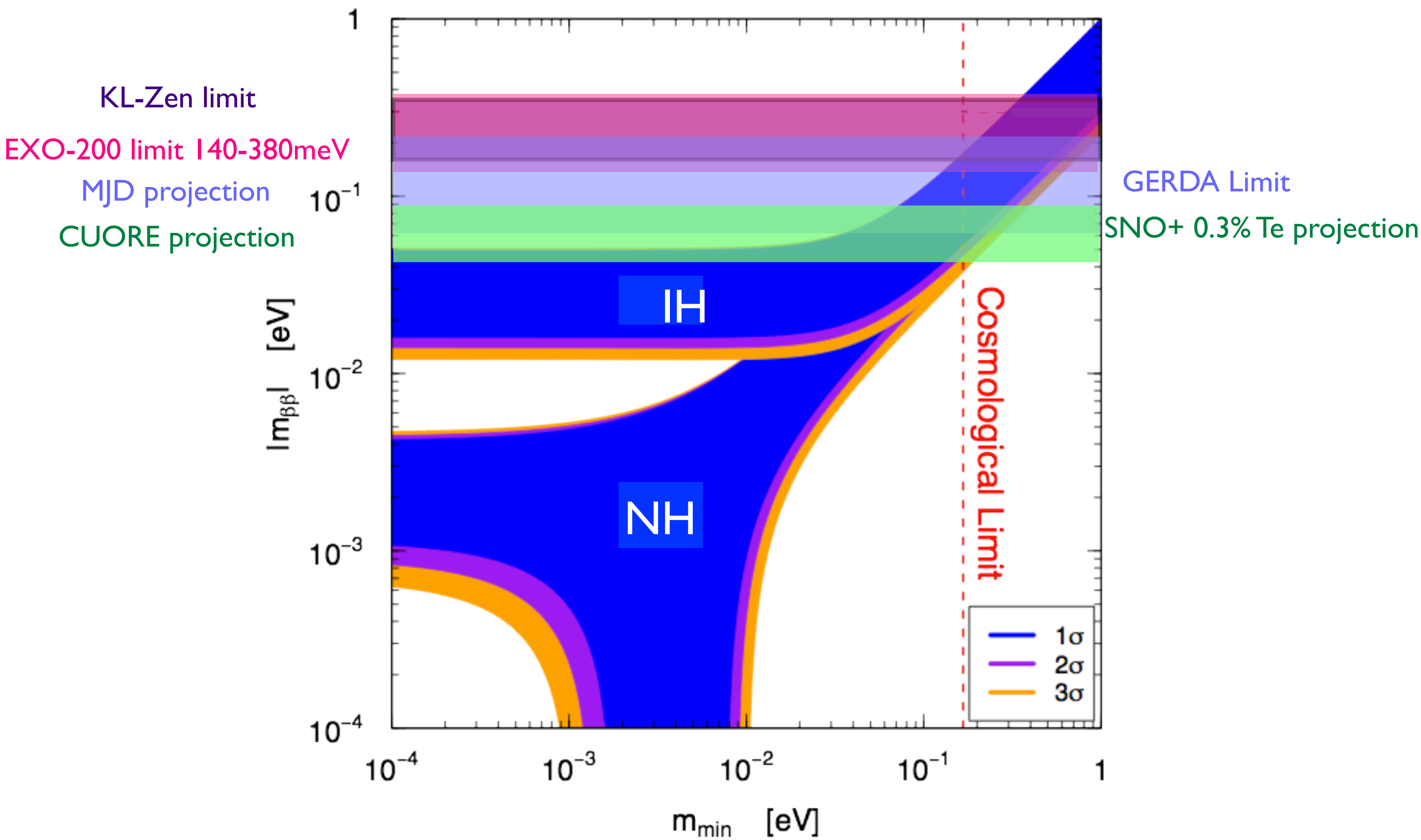
SuperNEMO



Tracking/Scintillator

Sensitivities and Some Projections

Caution: Depend on NMEs, background assumptions

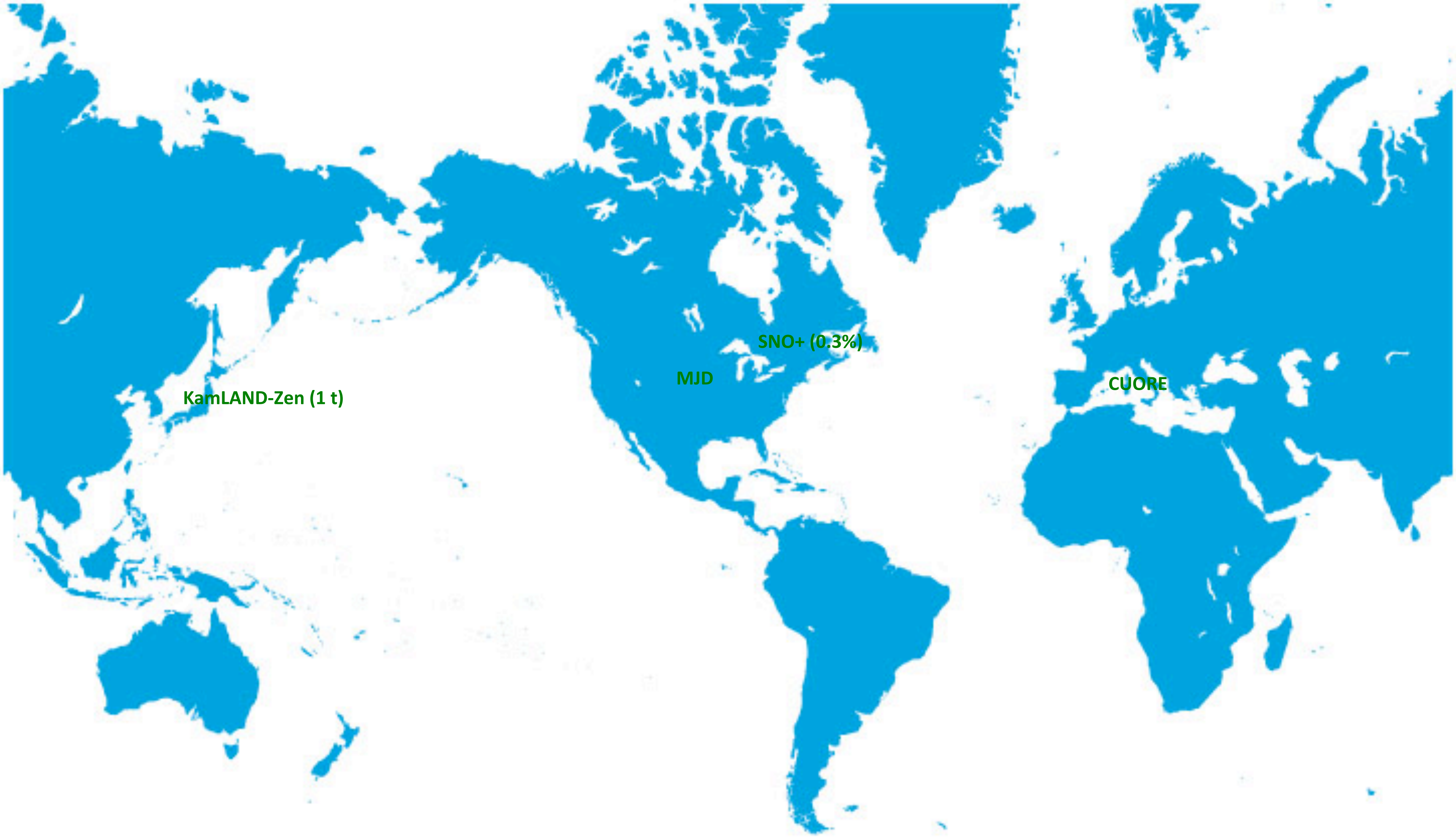


S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A27, 1230015 (2012)

Operating Experiments

US Involvement

Under Construction



US Involvement

Proposed or Under Development

Proposed or expected US Involvement

Going Beyond the "Tonne-Scale"

nEXO (5 t enriched Xe) looking at final sensitivities touching "normal hierarchy" region, possibly at SNOLAB. Can it go even bigger?

"Big and Dumb" tends to win out at large scales…

Probing Majorana neutrinos in the regime of the normal mass hierarchy

Steven D. Biller
Department of Physics, University of Oxford, Oxford OX1 3RH, UK

(published in Physical Review D, 071301R, 8 April 2013)

An approach to developing a feasible neutrinoless double beta decay experiment capable of probing Majorana masses in the regime of the nondegenerate normal neutrino mass hierarchy is proposed. For such an experiment, this study suggests that ^{130}Te is likely the best choice of candidate isotope and that metal-loaded liquid scintillator likely represents the best choice of detector technology. An evaluation of the required loading, scintillator properties and detector configuration is presented. While further development of Te-loaded liquid scintillator is required, recent progress in this area suggests that this task may not be insurmountable. This could open the door for a future experiment of unparalleled sensitivity that might be accommodated in a volume of the order of 10-20 kilotons. To the best of our knowledge, this is the first time that a potentially practical experimental approach to exploring Majorana neutrino masses in the nondegenerate normal hierarchy has been suggested.

How big a scintillation detector could plausibly be loaded and retain good optics?

$0\nu\beta\beta$ and "SNOWMASS"

DOE/ONP is "steward" of $0\nu\beta\beta$ program; OHEP will not support new projects here.

Some NSF support (e.g., CUORE) continuing.

NP plans suggest likely just one major new $0\nu\beta\beta$ project:

Based on Science:

- There are selected NP science targets of opportunity with the potential for high-impact in fundamental symmetries, neutrons, and neutrinos.
- These experiments may take on even greater significance depending on the results of accelerator research in the next few years
- To the extent there are resources to pursue them and they are complementary to HEP research, such opportunities may be pursued.
- For nEDM the science goal continues to be stronly motivated and R&D continues; a decision point is expected within ~ 2 years whether to proceed with the full experiment
- $0\nu\beta\beta$ experiments are sufficiently costly, a down-select to the best technology across HEP and NP makes sense and is planned.

T. Hallman

NSAC Sub-Committee on Scientific Facilities

NLDBD

Physics goal is to look for evidence of non-conservation of lepton number, which is required if NLDBD occurs. The lightness of neutrinos may be related to a very heavy mass scale beyond the reach of accelerators. This implies that neutrinos are "Majorana" particles, one and the same with their antiparticles. Lepton number would then not be conserved.

Experiments using several different isotopes are operating at the 100 kg scale. Going to the ton scale involves technical challenges, some of which have been resolved. R&D with respect to achievable backgrounds is still needed in most cases.

Projected costs cover a wide range, scattered about the $100M level.

We rank the Physics importance of at least one NLDBD experiment at the ton scale as "absolutely central".

We rank the Readiness of NLDBD experiments at the ton scale as "significant scientific/engineering challenges to resolve before initiating construction".

R. Redwine 3/8/2013

NSAC Sub-Committee on Scientific Facilities

Facility	Science	Readiness
ATLAS	a	
CEBAF	a	
RHIC	a	
EIC	a	b
FRIB	a	a
NLDBD	a	b

R. Redwine 3/8/2013

0νββ Facilities/Space Needs

Depends on detector and technology:

- KamLAND-Zen and SNO+ are stuck where they are.
- CUORE and SuperNEMO probably also in final resting place
- nEXO planning on SNOLAB, only site deeper is CJPL
- 1-ton Ge detector needed depth TBD

While long-lived cosmogenics can be significant backgrounds, these are primarily from surface exposure.

Neutron-induced events are difficult to estimate---fluxes and cross sections are not very well known.

Biggest competition for space may come from dark matter experiments (e.g. SNOLAB has space for maybe 2+1?)

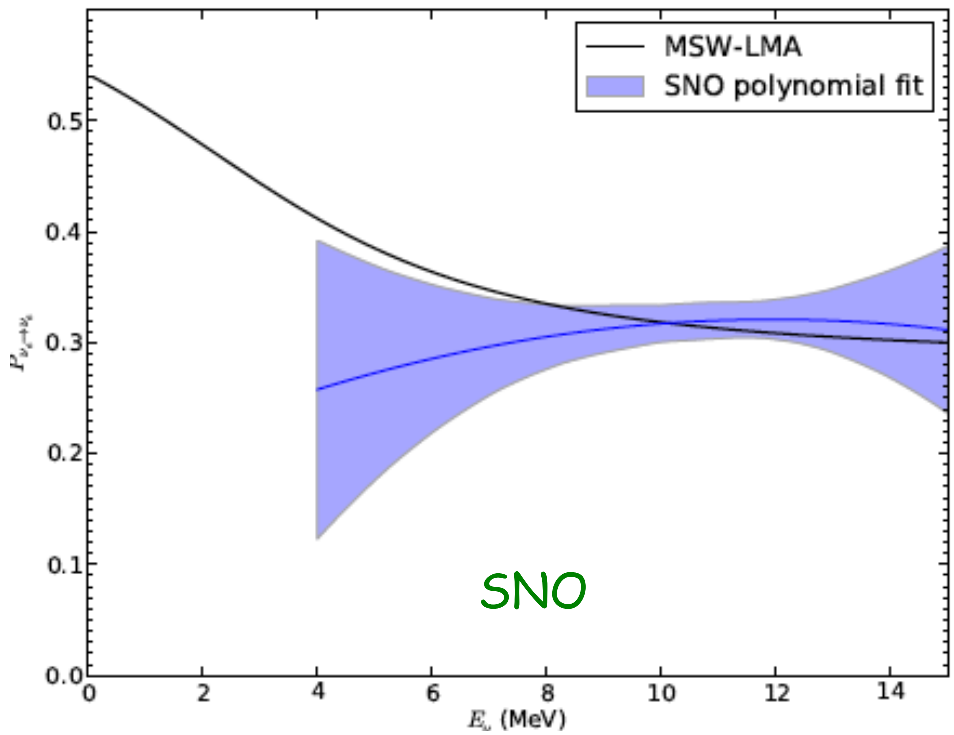
Other NP Experiments

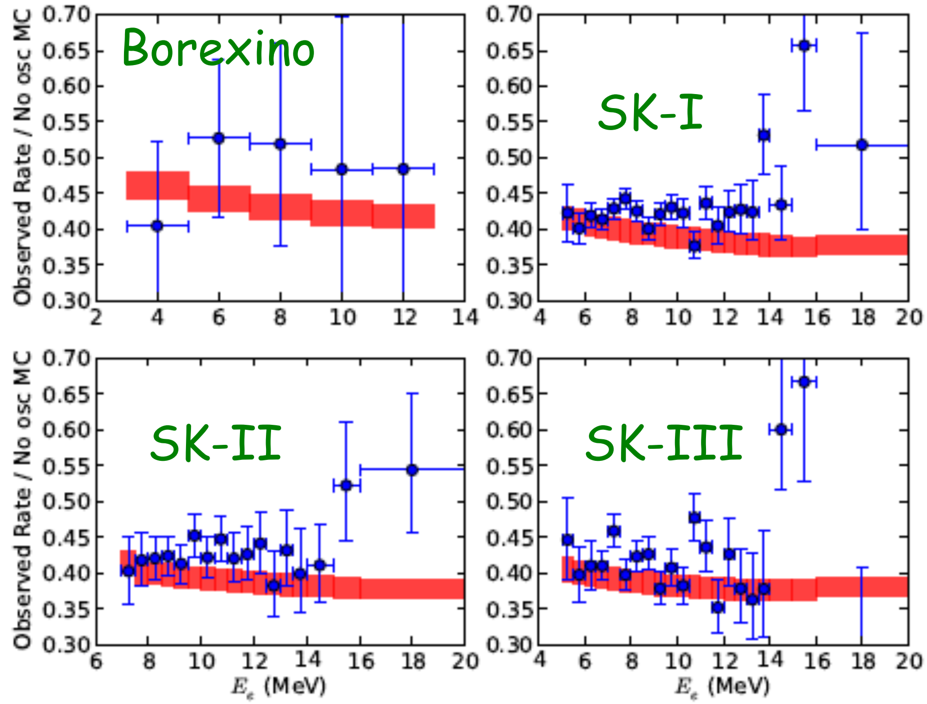
- Historically, solar neutrinos have been supported by both HEP and NP.
- Neither is committed to further funding other than collaterally (e.g, Super-K).
- Funding for a new project would likely come from NSF or NP, not HEP.

Other NP Experiments

Solar Neutrinos

Still interesting motivations:





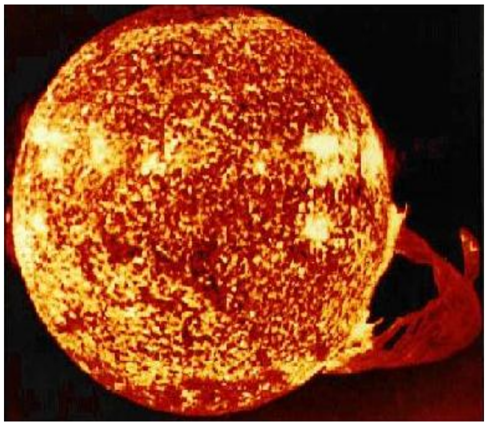
"Non-Standard Models, Solar Neutrinos, and Large θ_{13},"
Bonventre, LaTorre, JRK, G.D. Orebi Gann, S. Seibert, O. Wasalski

Transition region largely unexplored…tests for non-standard interactions.

Other NP Experiments

Solar Neutrinos

Still interesting motivations:



Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars. ---John Bahcall, PR, (1964)

- Helioseismology convinced `everyone' that SSM was correct
- Modern measurements of surface metallicity are lower than before
- Which makes SSM helioseismologic predictions wrong

But! CNO neutrinos tell us metallicity of solar core

$\longrightarrow$ Flux may differ by factor of 2 between old/new metallicity

(Maybe Jupiter and Saturn `stole' metals from solar photosphere?
---Haxton and Serenelli, Astrophys.J. 687 (2008)

Future Solar Experiments

LENS

$$\nu_e + {}^{115}In \rightarrow e^- + (\tau = 4.76\,\mu s)2\gamma + {}^{115}Sn$$

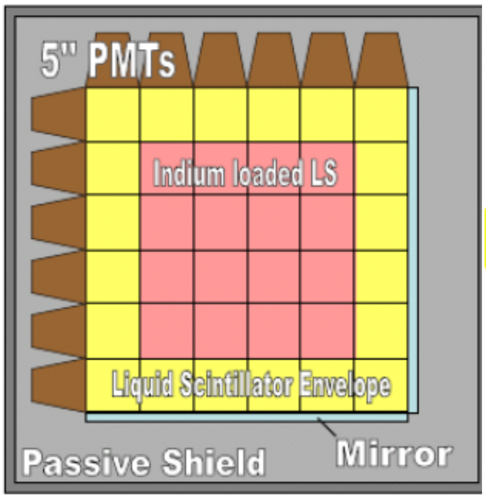
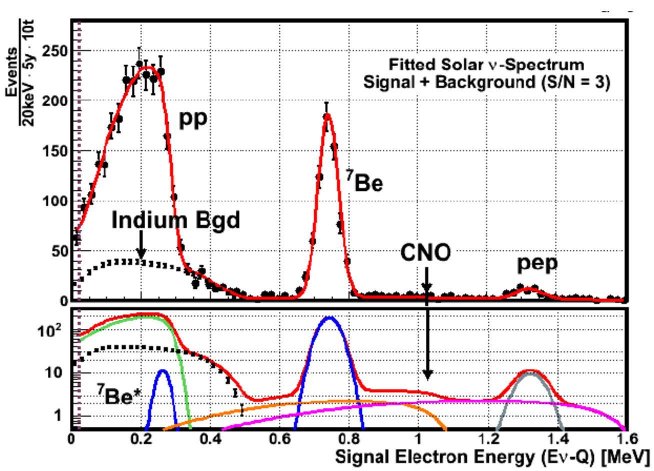
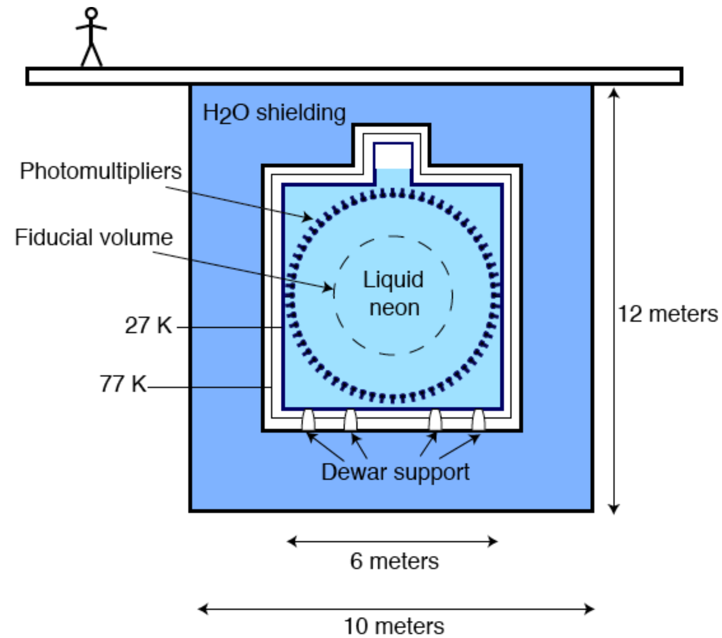


Fig. 12 Schematic design of MINILENS

CC reaction with Q=114 keV



CLEAN



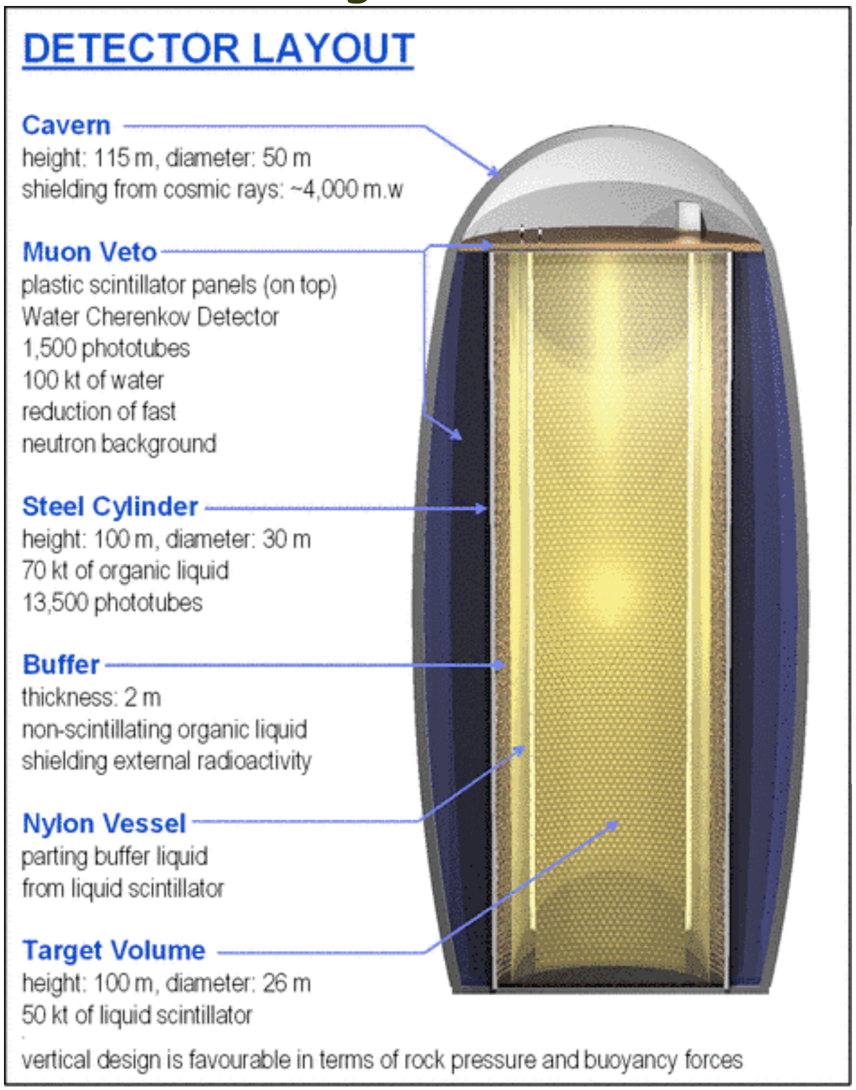
ES only but precision perhaps better than 1%

These need depth but not necessarily big size

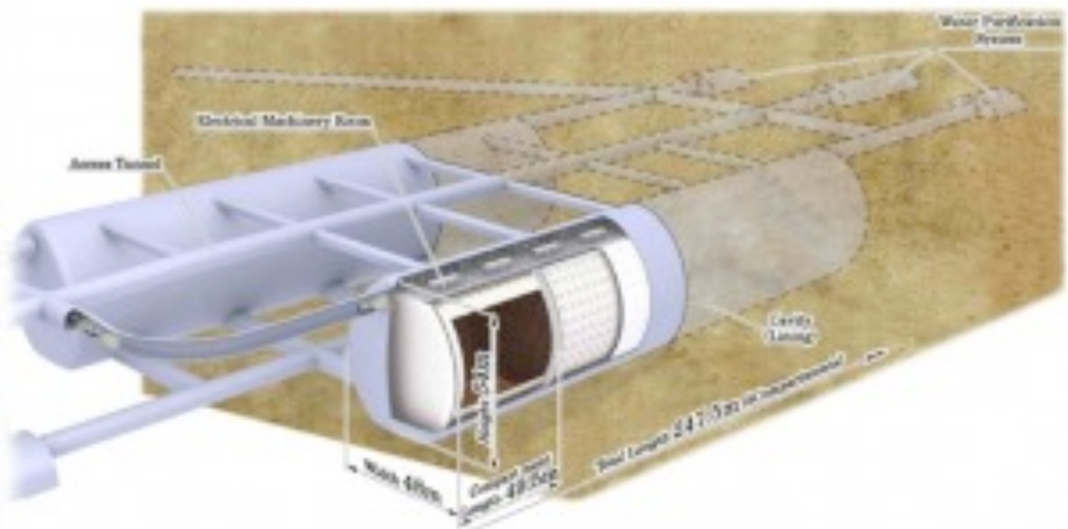
Future Solar Experiments

Very large liquid scintillator or H_2O detector

LENA---also geonu, DSNB…



Hyper-Kamiokande

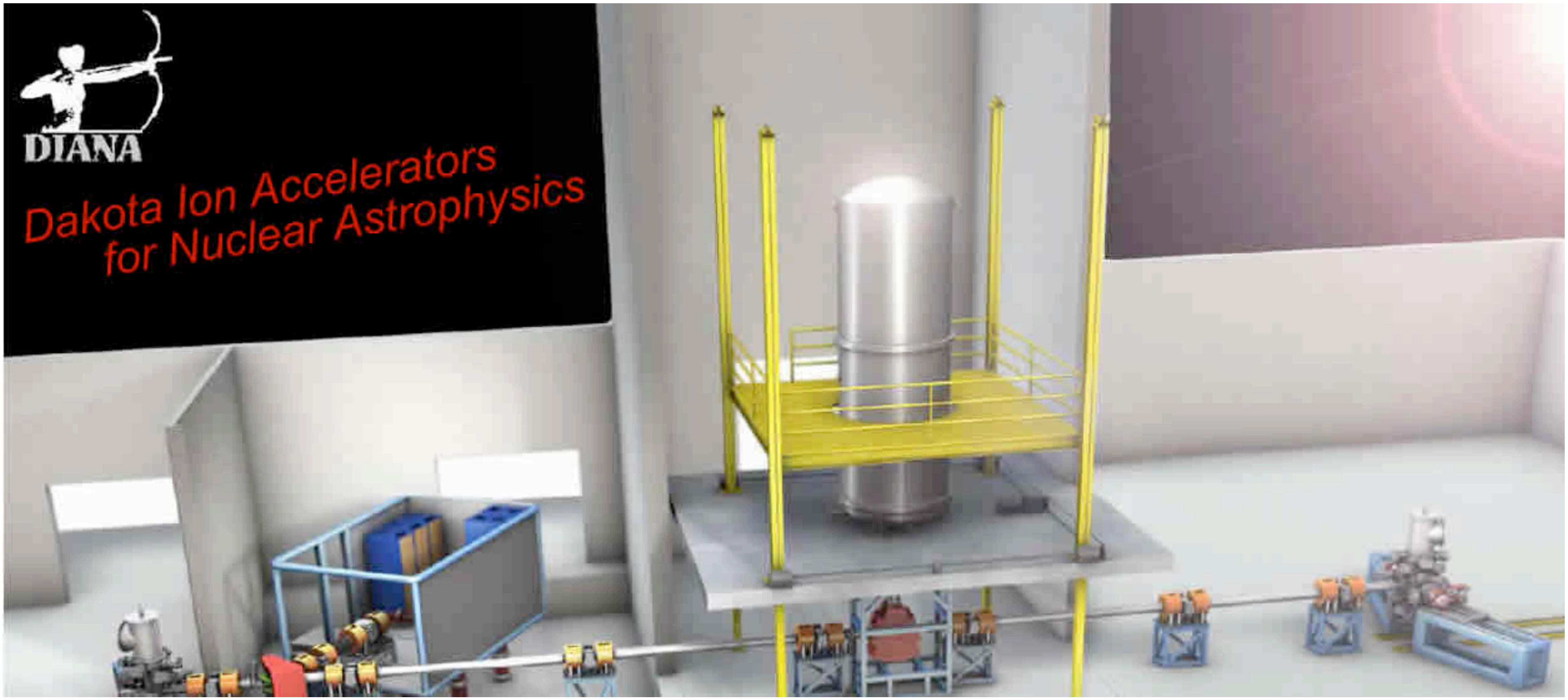


Depth and big cavities

Other NP Experiments

Nuclear Astrophysics

Measurements of stellar and supernova reaction cross sections:
Needs to be underground because of very rare-process meaurements



"Preferred" site is SURF; may have to be scaled down for cost or try another site.

Conclusions - $0\nu\beta\beta$/Low E NP

- Several $0\nu\beta\beta$ experiments already under construction at existing underground facilities, all but one outside US
- US involvement currently strong in many of these
- Next generation ("tonne scale") $0\nu\beta\beta$ experiments likely to be accommodated by existing and planned facilities, but may face competition for space from G2/G3-scale dark matter experiments
- Likely that there will be at most one next-generation $0\nu\beta\beta$ experiment with large US involvement, may or may not be sited within US
- Depth requirements for tonne-scale $0\nu\beta\beta$ experiments depends on technology choice and are not yet entirely known. New information may be available on 6-month to 2-year timescale.
- Path beyond tonne-scale experiments not well-defined but may require new underground spaces and perhaps facilities
- Broader low-E neutrino/nuclear physics experiments (large-scale solar n, geoneutrinos, low-E nuclear astrophysics) will require new underground spaces and perhaps facilities